

COMMENTS ABOUT THE USE OF X-RAY COMPUTED TOMOGRAPHY AS A PRECISION DIMENSIONAL METROLOGY TECHNIQUE

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Abstract: The X-ray computed tomography, first developed to image internal structures of the human body, and under permanent evolution, has become an important dimensional metrology suite. The extensive range of potential uses of the X-ray tomography in the industrial metrology, beyond the non-destructive inspection of materials, requires scientific metrology sense in order to produce proper measurement results. This paper outlines the first impressions about the use of X-ray computed tomography as a metrology tool, in the evaluation of products that comprise the precision engineering area.

Key-words: industrial metrology, multisensor coordinate metrology, X-ray computed tomography.

1. INTRODUCTION

The initial use of computed tomography for applications in radiological diagnostics during the seventies sparked a revolution in the field of biomedical engineering. Since then X-ray computed tomography has become an indispensable and integral component of routine work in clinics and medical practices. Through computed tomography, cross-sectional and non-superimposed images of the human body are delivered and used for medical diagnoses and treatment of head injury and body trauma or to detect tumors and other abnormalities. The main thrust behind the conception and continuous development of the computed tomography has always been the improvement of noninvasive and more efficient techniques for patient diagnosis.

Similar reasoning may be applied to the development of the X-ray computed tomography as an industrial metrology technique. The first application studies were devoted to the non-destructive inspection of mechanical components and parts. Discontinuities, cracks and voids could be detected without physically destroying or damage the sample under scrutiny. Recently X-ray computed tomography has been applied as an industrial measurement technique for the entire examination of inner and outer geometries of parts in a non-destructive manner.

Fig. 1 depicts the basic working principle of a 3-D X-ray measuring machine. On a fully protective enclosure, the object to be inspected, in the middle in Fig. 1, is rotated in the radiation field of an X-ray source, on the right in Fig. 1.

For a large number of beam directions, the intensity distribution of the radiation, after passing through the object, is determined by means of a flat panel detector, on the left in Fig. 1, and digitally stored as a projection. The resulting projections of the full rotation of the sample define the input data of the mathematical algorithms used for reconstructing the volumetric model of the measured object, which can be applied to different purposes.

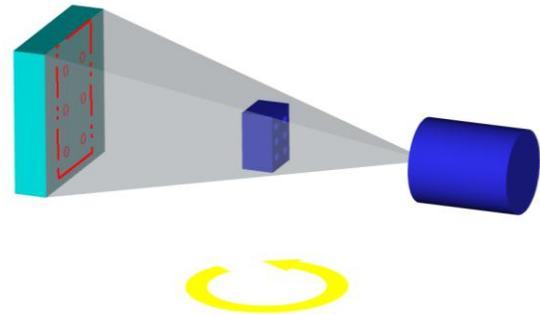


Fig. 1. Operation principle of a coordinate measuring machine with computed tomography [Courtesy: Werth Messtechnik GmbH]

The fusion of *computed tomography* and *precision dimensional metrology* emerges as a measuring technology capable of detecting internal features of complex parts, e.g., inner cavities and passageways resulting from casting and injection molding, and internal details and mechanisms of manufactured goods. The object imaging by 3-D X-ray computed tomography gives result to a very dense point cloud, which represents the volume model under investigation. Complete dimensional and geometrical assessment of the object structures, hidden or not, can be performed [1].

It becomes quite clear from the macro point of view the superposition of the coordinate metrology technology with the X-ray computed tomography. The integration of the two technologies, therefore, could be understood as a natural evolution of the concept of metrological tomography, because the particularities of each technology could be better explored. The multisensor coordinate measuring machines with X-ray computed tomography are part of a new and promising context of the precision dimensional metrology. Fig. 2 shows a classical measurement situation in

which the combination of X-ray tomography with measuring probes is essential to obtain suitable measurement results.

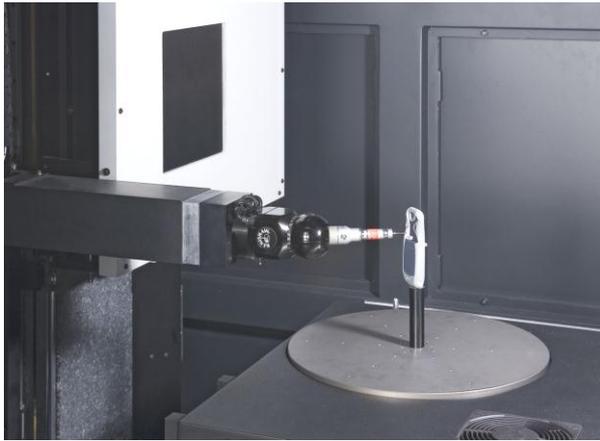


Fig. 2. Entire object measurement by X-ray computed tomography and functional-feature measurement refinement using a measuring contact probe [Courtesy: Werth Messtechnik GmbH]

Significant efforts have been undertaken by the Institute for Technological Research of the State of São Paulo - IPT in order to offer appropriate metrology solutions to already-known market demands and even to nowadays unknown demands. In this paper, the first measurements performed on multisensor coordinate measuring machines with X-ray computed tomography are illustrated and discussed. Details about the measurement of parts and components commonly found in the production environment are outlined, such as performance and operation issues and metrology challenges related to the X-ray computed tomography.

2. TOPICS OF CONCERN

The use of computed tomography based on X-rays as a dimensional metrology technique relies especially on recent developments such as: (a) micro-focus X-ray tubes; (b) detectors capable of capturing absorbed radiation levels with high resolution; (c) computers capable of processing and storing a large amount of data. The main contribution of the X-ray computed tomography as a precision dimensional measuring task is the fact that even hidden structures on the part can be evaluated. It is also worth of mentioning the simultaneous sampling of millions of points, impossible to be performed with a classical coordinate measuring machine on which each point is measured as a discrete event using different measuring probe arrangements, resulting in faster measurements.

Although the after-processing data obtained from X-ray tomography scanning contains similar information as that produced by a classical coordinate measuring machine, i.e., the coordinates of the sampled points, the uncertainty of the measurement result is composed of specific components. Since pure computed tomography does not involve relative translations between the sensor and the object during the measurement, but only the rotation of the part about an axis, the following elements might be found as critical in X-ray metrological tomography:

- (a) The selection of the X-ray tube voltage range depends on factors such as the object geometry and material. In

general, lower relative voltages apply to measurement of low density materials (e.g., plastic parts) and small objects; on the other hand, higher relative voltages apply to high density materials (e.g., metallic-alloy and metal parts) and large objects.

- (b) The position of the object under analysis has great effect on the quality of the volumetric model created and deviations observed. The relative orientation to the object rotation axis and the X-ray beam has been studied and identified as a significant factor mainly as a result of scattering artifacts. Surfaces parallel to the beam are not reproduced with the same quality as those surfaces oriented perpendicular to the beam.
- (c) The number of projection (angle increment) between two successive projections has direct impact on the time needed to collect the measurement data. As per the signal and system theory, more projections are recommended to increase the accuracy of the measured volumetric model. Studies have shown the observed deviations when performing more than 800 projections could enhance the results by less than 10% [2].
- (d) The reconstruction algorithm of the volumetric model from the 2-D projections is based on the assumption that an attenuation at a given point does not depend on the path traveled by the X-rays to reach that point. However, that is true only for a beam consisting of mono-energetic radiation. For multi-energetic beams, as X-ray beams, the radiation components of high frequency, due to their higher energy, are absorbed by the irradiated material at a lower proportion than those low frequency components. As a practical effect, for a large material thickness, the radiation components of lower energy can be partially or completely absorbed, and only the radiation components of higher energy reach the detector, i.e., the regions of the material that are influenced by the *beam hardening* are systematically measured (interpreted) as being larger [3,4,5].
- (e) The magnification is determined by the ratio of the source-object distance and the object-detector distance. Higher magnification levels result in lower volume resolution, reduce the observed deviations and, thus, reduce the measurement uncertainty. Larger objects can only be scanned with reduced magnification, since the object needs to be fitted always in the detector area.

Due to their special features the computed tomography technology has played a prominent role in the analysis of homogeneous materials (e.g., metals and metallic alloys, polymers, wood, concrete), in the fault analysis of multi-components objects (e.g., electronic devices, gap between thread diameter), and in the exploratory analysis of complex parts and components composed of one material or a mix of materials (e.g., fuel injection nozzles, orthopedic and dental implants, gas turbine blades).

3. TOMOGRAPHY-BASED MEASUREMENTS

In the coming subsections some computed tomography applications are shown and discussed from the metrological and operational point of view. The discussion is based on

the critical factors aforementioned and others specific to the studied cases: (a) measurement of a plastic component and attributive inspection of parts; (b) measurement of a metallic component; (c) measurement of an object composed of two or more materials.

Using metrological tomography with relative translation, parts larger than the measurement volume in the chosen magnification can be measured by combining several partial images of the object with coordinate measuring machine accuracy. Measuring details that are distributed over the entire dimension of even large parts in highest resolution is another advantage of the so-called raster tomography. More details about this measurement algorithm will be presented.

3.1. Tomography of plastic materials

The first X-ray tomography measuring machines were devoted to the evaluation of plastic materials, basically due to the lower energy required to pass through the material and the limits imposed by the technology at that time, mainly those related to the X-ray reflection.

Usually the measurement (and exposure) time is reduced in relation to more dense materials since fewer projections are necessary to produce a representative volumetric model. For example, the entire characterization of an asthma inhaler device has been made possible by tomography. Usually no special clamping device is needed, although some attention has to be paid to the sample orientation on the rotary table. Depending on the measurement accuracy required and the shape and inner details of the object, the machine setup may take a considerable time.

Fig. 3 (left) shows the point cloud of the asthma inhaler after reconstructing the volume model from the tomography dataset. The point cloud can be compared with the nominal mathematical model and the actual deviation determined for inspection purposes. Fig. 3 (right) exhibits the color-coded view of the asthma inhaler under investigation.

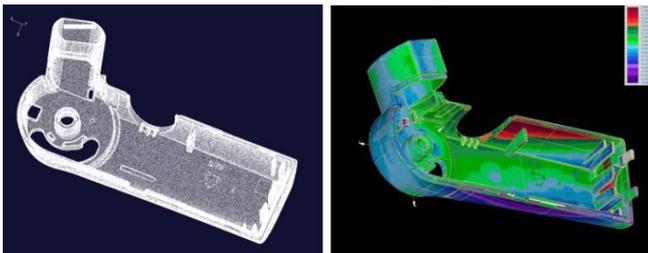


Fig. 3. Point cloud of an asthma inhaler generated by tomography (left) and the corresponding color-coded representation of deviation against the CAD model (right)

In a pre-production context the information as illustrated in Fig. 3 (right) would enable correcting injection-molding tools and thus reducing development and production costs (e.g., rework and scrap). The typical measuring accuracy on the order of a few micrometers for tomography of low density materials is sufficient for many applications in the plastic sector where tolerances in the range of tenths of a millimeter are usually encountered.

The raster tomography tool available on the multisensor coordinate measuring machine makes possible virtually expanding the detector area and therefore inspecting larger

parts. Partial images of the object are taken and merged together in order to compose larger scanned high resolution images.

3.2. Tomography of metallic materials

The scanning of metallic materials by X-ray computed tomography demands higher X-ray power to pass through them. Considering objects of similar shapes - thickness as well, much more X-ray power is required to scan steel parts than aluminum parts. Consequently, the thickness measuring threshold is considerably larger for aluminum parts than for steel parts.

The definition of proper measuring parameters which are dependent on the object thickness, however, is not a trivial task. That is because the wall thickness of a given part may display variations as a function of the object geometry. For metals and metallic alloys, mechanical filters are normally necessary to enhance imaging quality. The complexity of the workpiece geometry can affect the measurement accuracy if the object is not properly positioned.

Considering that metal materials may reflect part of the visible light and that X-rays are electromagnetic radiations, of the same nature as visible light, X-rays may be similarly reflected when crossing the material. The object geometry and the relative orientation to the X-ray beam may produce undesirable reflections which introduce inaccuracies to the measurement results.

The combination on the same machine of tomography with multiple measuring sensors is a manner of increasing the measuring accuracy. The evaluation of micro-holes on fuel injection nozzles for diesel engines may be brought to the micrometer range when using a tactile scanning probe for correcting tomography datasets. Fig. 4 illustrates the so-called fiber probe while measuring injection nozzle micro-holes and the results displayed as a point cloud and a color-coded map.

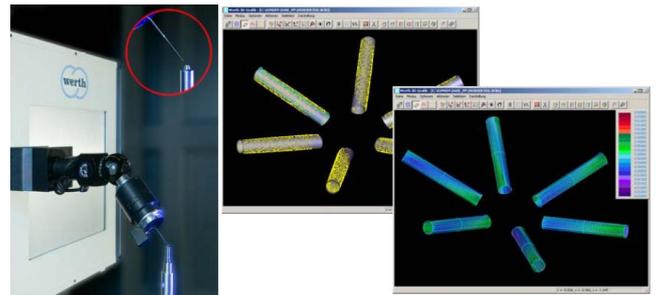


Fig. 4. Diameter and form measurement of the injection nozzle holes with X-ray tomography and optical-tactile probe (from left to right: fiber probe measurement; point cloud after correction; color-coded view of the measured deviations against CAD)

In order to evaluate the reproducibility of tomography measurements, the same injection nozzle micro-holes were measured on two similar multisensor coordinate measuring machines with X-ray computed tomography. The diameter estimated for each position along the hole axis is shown in Fig. 5 (five trials on each machine). One can notice that the measurement reproducibility is in the range of about 1 μm . The largest diameter deviation was observed at position $z = 620 \mu\text{m}$ (ca. 1.35 μm).

For many applications that error would not be an issue. In order to measure parts with tolerance zones of hundreds of a millimeter (or even less), however, the reproducibility would be a relevant factor to the measurement uncertainty. In such a scenario, some techniques would be necessary to reduce systematic effects. On the other hand, prior to correct them, the measurement consistency needs to be checked.

From Fig. 5 one can also observe that the measurements with the same tomography-based machine have not differed by more than 0.5 μm in average. For this particular case, the average hole diameter at each position could be corrected with an intrinsic uncertainty down to 0.1 μm (not including other influence factors).

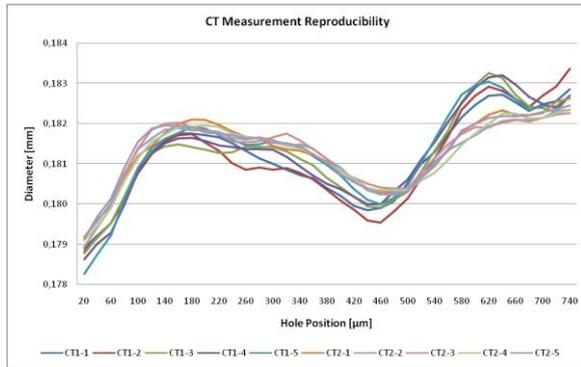


Fig. 5. Measurement reproducibility of two multisensor coordinate measuring machines with X-ray tomography when measuring the same features on the same part

The discrepancies between tomography measurements and the reference measurements with the fiber probe for the pattern of holes lied within the range of 3 μm , as shown in Fig. 6. This deviation could be definitely neglected in some measurement cases. For other measurements, the significant bias needs to be corrected. The auto-correction algorithm of the multisensor coordinate measuring machine with X-ray tomography allows adjusting the raw tomography values to the reference values.

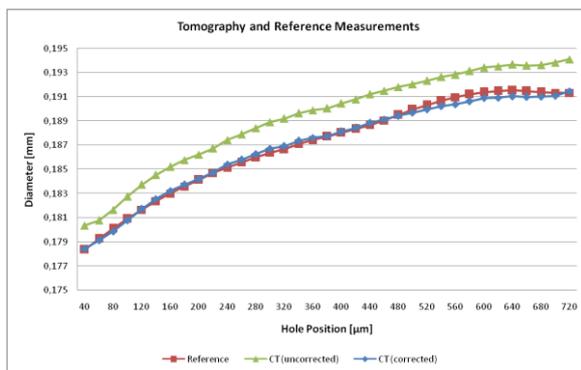


Fig. 6. Feature size along the hole axis for uncorrected tomography measurements and corrected tomography measurements using as reference the fiber probe

Depending on the part geometry and material, as well as the X-ray tomography parameters, many different artifacts like beam hardening or scattering may influence measuring results. They are influenced by the radiography length and the aspect ratio (shortest to longest length to be measured).

For the case here-described, the conical form of the injection nozzle micro-holes may lead to more or less artifacts and therefore affect the accuracy.

After correcting the tomography data based on the fiber probe measurements, all deviations lied within the range of 1 μm as shown in Fig. 7. Hence, for very critical measuring tasks such as the evaluation of micro-features of an injection nozzle made of a steel alloy one can estimate the feature size with deviation on the order of tenths of a micrometer.

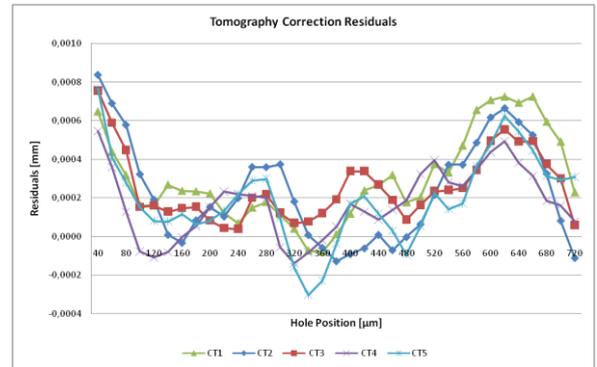


Fig. 7. Difference between corrected tomography values and fiber probe measurement values on five runs for each hole position

By comparing and correcting raw tomography dataset against reference measurements with a fiber probe, one can have tomography results traced back to the SI unit of length. For the specific case of micro-holes, the diameter might be known with even lower uncertainty if a calibrated ring of similar size is also measured and correction value applied.

3.3. Tomography of inhomogeneous materials

Manufactured goods that require assembly inspection are defined in this paper as inhomogeneous materials. Electrical appliances and electronic devices, electro-medical devices, and computer devices are some examples of inhomogeneous materials. Computer tomography scanning of components with more than one material requires the use of filters and longer exposure and measuring time.

The task of visualizing and inspecting a titanium implant in a bone is described. Fig. 8 shows the local tomography of a section of the implant. In order to improve measurement quality, the effective region of interest of the object can be scanned with better discrimination by tomography.

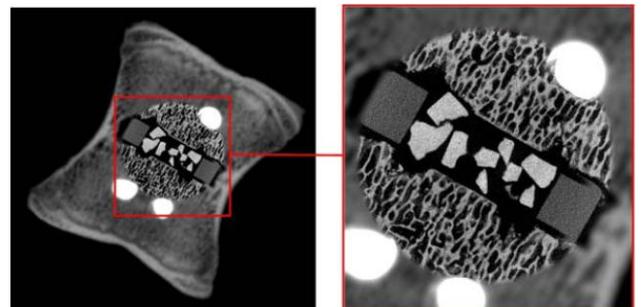


Fig. 8. Local tomography applied to capturing interior details of an implant in a bone

The local tomography is undertaken by first sampling the entire object at a lower magnification and, therefore, a lower resolution. Volumetric information is then available for all areas of the object in a coarse *voxel* raster. The region of interest is then recorded by tomography at maximum magnification and resolution. When the higher resolution area is reconstructed, the missing *voxel* data is calculated from the images scanned at the lower resolution and included in the back projection calculation. Using such a technique, the position of the implant in the bone shown in Fig. 8 could be estimated in the range of a few micrometers.

4. DISCUSSION AND CONCLUSION

The X-ray computed tomography defines a technology milestone of the precision dimensional metrology. Countless measuring possibilities have been revealed and allowed new developments in many business sectors. For instance, the dimensional, geometrical and functional evaluation of gas turbine blades, essential part of the development process of more efficient components, is only possible with the X-ray metrological tomography.

From the point cloud it is possible to gather information about hidden structures of the sample, such as cracks and voids. The same point cloud can be used to evaluate the size and geometry of the object, including the comparison of the measured points against the nominal mathematical model, which may benefit product development and manufacturing phases. Reverse engineering of systems and components is another application of X-ray computed tomography.

Some practices of handling, reducing or correcting some influence factors were presented and discussed in this work. However, the list of influence factors is quite extensive. Questionable measurement results may be obtained in certain cases. That means specific strategies to extract more reliable results of tomography measurements need to be continuously conceived as the range of application of the technology increases.

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